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Multiobjective Automotive Drive By Wire Controller Design.

Jose C. Zavala, Paul Stewart and Peter J. Fleming

Abstract— **The presence of flexibility in automotive drivelines, coupled with nonlinear elements such as gear lash leads to the presence of an undesirable oscillatory response to step changes in throttle input. This oscillation is generally low frequency (approximately 2 to 5 kHz) and can be of sufficient amplitude to cause driver discomfort and subjective disappointment with the driveability of the vehicle. A pole placement controller is developed for a "drive by wire" (electronically operated throttle) system, with the objective of reducing or eliminating the oscillatory response. Due to the inherent nonlinearities present in the system and the various constraints which must be applied to the controller design, the polynomial values for the pole placement controller are selected by the application of multi objective optimisation**

Keywords— **Pole Placement, Drive by Wire, Multi Objective Optimisation, Automotive, Driveability**

I. Introduction

This paper documents the controller design for a low cost electronic throttle actuator and microcontroller development to control vehicle oscillation. A feasibility study had been carried out on a vehicle fitted with the electronic throttle system (Stewart and Fleming, 2001,2002) to confirm the performance potential of such a system. Drive by wire applications for the replacement of the conventional cable link between the throttle pedal and the throttle body are now the focus of development by many major automotive manufacturers. By fitting a stepper or permanent magnet servo motor (Stewart and Kadirkamanathan, 1999) to the throttle body, and an electronic throttle pedal with potentiometer, a "drive-by-wire" system can be implemented by a microcontroller or DSP. Sophisticated control algorithms can be added to the operation of the throttle actuator (Stewart and Kadirkamanathan, 2001). Control systems have been designed (Rossi, Tilli and Tonielli, 2000) which allow fast and accurate response to changes in pedal demand, and have been shown to possess robust operating characteristics. Current trends indicate that electronic throttle control and variable valve timing are the most powerful tools in the control of vehicle "driveability" (Azzoni, Moro, Ponti and Rizzoni, 1998), (Stefanopolou, Cook and Grizzle, 1995). A torque controller is designed and implemented in this paper to shape the vehicle response to the first torsional mode of the driveline. The initial requirement is to damp the oscillations generated by throttle "tip-in" (step throttle input). This dynamic mapping is constrained by the requirement to maximize the vehicle acceleration response available to the throttle, and also to accommodate other aspects of driveability, such as minimizing subsequent oscillations during tip in. Control analysis and design for this automotive system is complicated by a various factors. There are a number of nonlinearities present, such as backlash in the gearbox, a tyre model which varies nonlinearly with road speed, and nonlinear clutch response. Also, a significant process lag is present between throttle actuation and torque production due to manifold fill delay. Finally, a nonlinear engine torque-speed mapping exists. Experimental open-loop data was available from a test car which was fitted with a data acquisition system including three axis accelerometers. A V6 engined saloon vehicle was loaned for the purpose of analysis, design and testing. A systematic excitation of the driveline was made experimentally on the vehicle by performing step demands in all gears at discrete points throughout the effective engine speed range of the vehicle, allowing the validation of a dynamic model which had been developed in *Matlab and Simulink*. A representative experimental response is

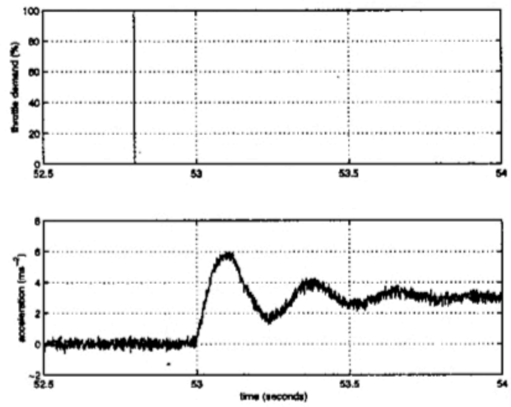

Fig. 1. Vehicle acceleration step response in second gear at $10ms^{-1}$.

shown in figure 1. Particular note should be taken of the significant response time delay, and the under-damped acceleration profile which can lead to driver dissatisfaction with the perceived smoothness of the overall vehicle response.

Paul Stewart is with the Electrical Machines and Drives Group in the Department of Electrical Engineering, University of Sheffield, Mappin Street, Sheffield S1 3JD U.K. E-mail: p.stewart@sheffield.ac.uk, Tel: +44 (0)114 2225841, Jose C.Zavala and Peter J. Fleming are with the Department of Automatic Control and System Engineering, University of Sheffield.

Cancellation of driveline oscillations has been studied using several methods. Generalised optimal control theory has been aplied (Best, 1998), however, the oscillation in the controlled acceleration response was found to be still significant because of the presence of lash nonlinearities. Fuzzy control has been proposed (Wiley, 1999), yet stability was found to be a major concern. Pole placement strategies have been used (Richard, Chevrel, de Larminat and Marguerie, 1999), but acceleration response still remained open to considerable improvement, due to the difficulty of ascertaining the controller polynomial values. This does suggest that progress might be made if the correct controller values could somehow be chosen.

The objectives of the controller design will be to reduce or eliminate both the overshoot and subsequent oscillation of the vehicle acceleration during throttle step demand, while attempting to maintain the open loop acceleration rise time. The controller design can be best assessed in 2nd gear as this gear demonstrates the worst case oscillations. The pole placement approach will be further developed by using Multi Objective Genetic Algorithms (MOGA) to choose the controller polynomial values.

II. Pole Placement

The prime objective of the pole-placement design method is to design a closed loop system with specified poles and thus the required dynamic response. The resulting characteristic equation will determine the features of the system, such as rise time, overshoot and settling time. The system model and its linear controller can be expressed respectively as

$$A(s)y(s) = B(s)u(s) \tag{1}$$

$$S(s)u(s) = T(s)u_c(s) - R(s)y(s) \tag{2}$$

where $A(s)$ and $B(s)$ are polynomials in the Laplace domain and $u(s)$ is the control variable. $S(s)$, $R(s)$ and $T(s)$ are the error, feedback and feedforward controller polynomials in the complex domain (figure 2). The controller has two inputs: $u_c(s)$, which is the command signal and $y(s)$, the measured output. Three constraints are associated to the model: the degree of $B(s)$ is less than the degree of $A(s)$, there are no common factors between polynomials $A(s)$ and $B(s)$, and $A(s)$is a monic polynomial. From equations 1 and 2, the characteristic

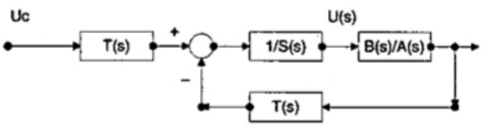

Fig. 2. Pole placement driveline controller.

equation of the closed loop system will be

$$F(s) = A(s)S(s) + B(s)R(s) \tag{3}$$

The objective of the pole placement design is to find polynomials $S(s)$ and $R(s)$ that satisfy equation 3 for specified $A(s)$, $B(s)$ and $F(s)$. Equation 3 is known as the *Diophantine equation* and can be solved if the polynomials do not have common factors and the system is proper (Astrom and Wittenmark, 1997). The Diophantine equation can be solved using a linear matrix. By expanding both sides of equation 3 and equating equal powers of the complex variable s, the equation can be expressed in a set of linear equations,

$$\begin{vmatrix} a_0 & 0 & 0 & \dots & 0 & b_0 & 0 & 0 & \dots & 0 \\ a_1 & a_0 & 0 & \dots & 0 & b_1 & b_0 & 0 & \dots & 0 \\ a_2 & a_1 & a_0 & \dots & 0 & b_2 & b_1 & b_0 & \dots & 0 \\ \vdots & \vdots & \vdots & \dots & \vdots & \vdots & \vdots & \vdots & \dots & \vdots \\ a_N & a_{N-1} & a_{N-2} & \dots & a_0 & b_N & b_{N-1} & b_{N-2} & \dots & b_0 \\ 0 & a_N & a_{N-1} & \dots & a_1 & 0 & b_N & b_{N-1} & \dots & b_1 \\ 0 & 0 & a_N & \dots & a_2 & 0 & 0 & b_N & \dots & b_2 \\ \vdots & \vdots & \vdots & \dots & \vdots & \vdots & \vdots & \vdots & \dots & \vdots \\ 0 & 0 & 0 & \dots & a_N & 0 & 0 & 0 & 0 & b_N \end{vmatrix} \begin{vmatrix} x_0 \\ x_1 \\ \cdot \\ \vdots \\ x_{Nx} \\ y_0 \\ \cdot \\ \vdots \\ y_{Ny} \end{vmatrix} = \begin{vmatrix} c_0 \\ c_1 \\ \cdot \\ \vdots \\ c_x \\ \cdot \\ \cdot \\ \vdots \\ c_{Nc} \end{vmatrix} \tag{4}$$

where N denotes the maximum between n_a and n_b. Equation 4 is known as the Sylvester matrix. The number of unknowns is given by the number of coefficients in Ss and $R(s)$, and is equal to $n_s + n_r + 2$. The number of equations is $n_c + 1$, where n_s, n_r and n_c are maximum degrees of $R(s)$ and $F(s)$ respectively. According to Sylvester's theorem, if $A(s)$ and $B(s)$ are coprime, then $S(A, B)$ is non-singular. There is a unique solution for $F(s)$ in equation 3 if (Richard, et.al., 1999)

$$\begin{aligned} n_s + n_r + 2 &= n_c + 1 \\ &= max(n_a + n_s, n_b + n_r) + 1 \end{aligned} \tag{5}$$

Introducing α and β as the difference in the relative degree of $\frac{B(s)}{A(s)}$ and $\frac{R(s)}{S(s)}$ respectively gives

$$\alpha = n_b - n_a \qquad \beta = n_s - n_r \tag{6}$$

The objective is now to find an expression for n_c. Using equations 6 and 6, leads to two cases for its calculation, which depend on the result of the operator max(). For the first case $n_a + n_s > n_a + n_s - \alpha - \beta$ derives in $\alpha + \beta > 0$. The order of the controllers will then be

$$\begin{aligned} n_s &= n_a + \beta - 1 \\ n_r &= n_a - 1 \\ n_c &= 2n_a + \beta - 1 \end{aligned} \tag{7}$$

For the second case, it is possible to see that if $n_a + n_s < n_a + n_s - \alpha - \beta$, then $\alpha + \beta < 0$, however for design purposes, that possibility will not be explored here.

III. Genetic algorithm optimisation of controller design

Two major questions arise with the use of the pole placement design, firstly what is the optimum location of the poles for the characteristic equation of the controller, and secondly how many poles must be placed? Resolving the issue may be a matter of trial and error if the system is complex and there is noise in the feedback signals or (as it is the case of the driveline) there are nonlinearities, such as delays and saturation curves (Richard, et.al., 1999), (Astrom, 1997). The problem of selecting the optimum pole locations will be addressed using genetic algorithms. Its use may seem contrary to the aim of the structured analytical methods of generating a precise knowledge of a system and applying a well defined control rule, however, the presence of uncertainties and the lack of a deep knowledge of the particular system represent an obstacle that genetic algorithms are likely to overcome. An important aspect of the genetic algorithm is that its application gives us a more deep understanding of the problem and its results may not necessarily be in our original scope of solutions. Genetic algorithms (GA's) are stochastic optimisation procedures whose search methods model the natural selection and inheritance process. The main concepts on GA's are due to (Holland, 1975). More recent publications by (Goldberg, 1989) and (Michalewicz, 1999) provide a complete examination and introduction to GA's. The underlying principle that supports GA's is the survival of the individuals (potential solutions) according to their fitness (or abilities to solve a particular problem). For each generation, a new set of individuals is created by breeding the best individuals from previous generations. This process results in the evolution of whole populations in which individuals are better suited to their environment than the individuals that they are created from. The fact that the GAs operate in parallel over a given population makes it possible to evaluate multiple objectives for each of the individuals. This approach is called Multi Objective Genetic Algorithm (MOGA) and is required in many applications where competing objectives are to be optimised. The result of optimising such problems is usually a set of equally valid, nondominated solutions. The union of all those points is known as the Pareto-optimal set. In MOGA, several steps are required: ranking to estimate performance of the population; selection to obtain a population for each generation; and mating to produce new individuals. Fitness sharing and mating restriction techniques can be used to improve the results (Chipperfield, Fleming, Polheim). The results of an optimisation can be viewed and analysed with a trade-off plot, which shows the competition of the different objectives. If we consider the simplified driveline model in figure 3, the input of the system is the engine torque

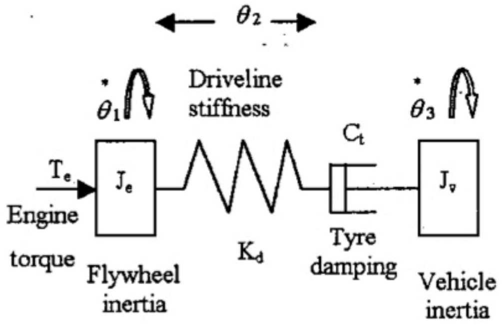

Fig. 3. Second order driveline model.

T_e and the output or measurement that concerns this paper is the vehicle velocity, which in this case is given by the vehicle equivalent angular velocity $\dot{\theta}_3$ multiplied by the radius of the wheels. However, it must be borne in mind that the final objective is to control the acceleration through the use of drive-by-wire to control the engine torque. Using the equations that characterise the simplified linear system in figure 3, and the specific parameter values of the drivetrain, the polynomials $B(s)$ and $A(s)$ can be obtained.

$$\frac{v(s)}{u(s)} = \frac{B(s)}{A(s)} = \frac{1615.7}{s^3 + 4.3s^2 + 521.8s} \tag{8}$$

where $V(s)$ is the vehicle velocity, $u(s)$ is the engine torque, and $B(s)$ and $A(s)$ are the polynomials representing the transfer function. The model in equation 8 gives a very good approximation of the open loop response of the driveline validated model. As part of the driveline model , a second order Pade approximation will be added to equation 8 to model the delay featured in the driveline. The resulting polynomials were

$$\frac{B_1(s)}{A_1(s)} = \frac{B(s)P_{num}(s)}{A(s)P_{den}(s)} \tag{9}$$

where $A_1(s)$ and $B_1(s)$ are the new polynomials representing the system and $P_{num}(s)$ and $P_{den}(s)$ are the numerator and denominator respectively of the Pade approximation. The order difference in the process polynomials is $\alpha = n_a - n_b = 5 - 2 = 3$, and defining $\beta = 0$, the order of the controllers $S(s)$ and $R(s)$ and the closed loop characteristic equation $F(s)$ can be found as in equation 7. Then, $n_s = 4$, $n_r = 4$ and $n_c = 9$. This leads us to the matter of determining the value of nine roots for the characteristic equation.

The use of MOGA in the search for an optimal controller requires first to choose a set of decision variables, e.g. features that will affect the behaviour of the system. A suitable type of coding must be proposed for those variables. The objectives, or variables to assess the system have also to be defined and an objective function must be proposed to evaluate each individual. The controller's performance is evaluated by simulating the model of the system using a step input to the system.

The pole locations will be the decision variables in the MOGA, since those are the unknowns in equation 3 and will be used to calculate directly the values of the coefficients for the polynomials $R(s)$, $T(s)$ and $S(s)$. The gain of $T(s)$ will also be included as a decision variable. The coding of the variables was real, since that allows more natural data handling and is more efficient. The objectives set the goals to reach and ensure that every selected individual satisfies the specifications. In this particular implementation of MOGA, the selected features were related to the performance of each individual: settling time, steady state error, rise time, sum of coefficients and control signal power. These features were selected in order to find solutions that satisfy the performance requirements without forcing the system to behave in a particular unnatural manner. The use of the damping factor as an objective, for instance, would have resulted in the assessment of a higher order response with a second order parameter. The objective function on the other hand realises the following actions: - Receiving the parameters passed by the genetic algorithm (genotype). - Generating a controller. - Simulating the nonlinear model. - Measuring the performance of that particular solution. Even though the implementation of genetic algorithms does not require a precise knowledge of the application, the selection of the adequate parameters may take a few trials.

A novel Gaussian mutation operator was included in the mutation stage in order to improve the optimisation in the borders of the search space. This operator changes the mutation probability rate of an individual when it is close to the borders of the search space, avoiding a non-uniform statistical process of mutation, that could otherwise bias the search. The initial conditions for the driveline nonlinear model were changed randomly each generation, in such a way that the best controllers are the ones that could perform adequately under wide system parameter variations. This approach was intended to achieve as far as possible, a robust controller. Finally, the minimisation of the control energy was included amongst the objectives in order to achieve a feasible, efficient controller.

IV. Results

The execution of the MOGA was initiated to derive an optimal driveline controller. The objectives and their priority levels were set as follows: settling time: 3; steady state 2; rise time: 1; sum of coefficients: 0; signal power: 1. Thus the settling time (the main priority of this design) was assigned a higher priority than (for example) the control action required to achieve the damping of oscillations. The algorithm produces a non dominated set of candidate solutions which achieve to varying levels the competing design and dynamic performance criteria. A candidate solution was chosen which achieved acceptable levels of oscillation, coupled with a risetime which retained the feeling of "sportiness". The acceleration responses of the vehicle for two different initial conditions are shown in Figures 4 and 5: The

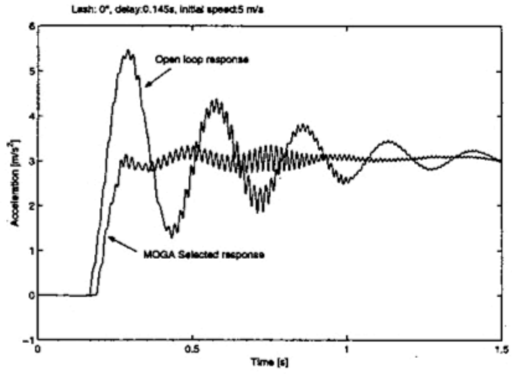

Fig. 4. Vehicle acceleration response, lash=0, delay=145ms, initial speed=5m/s

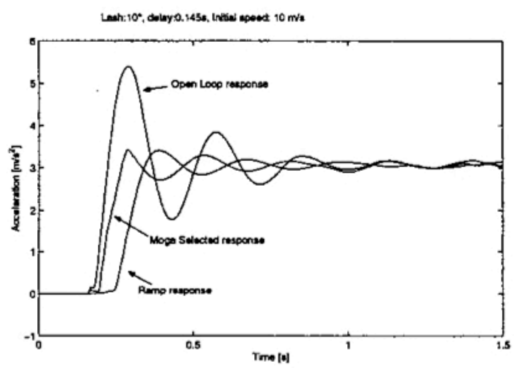

Fig. 5. Vehicle acceleration response, lash=10°, delay=145ms, initial speed=10m/s

selected controllers were

$$
\begin{aligned}
R(s) &= s(s-20.1+12.1i)(s-20.1-12.1i) \\
&\qquad (s-17.3) \\
S(s) &= (s-167.8)(s-41.3+103.2i) \\
&\qquad (s-41.3-103.2i)(s-18.6) \\
T(s) &= (s-40.6+3.3i)(s-40.6-3.3i) \\
&\qquad (s-37+1.71i)(s-37-1.71i)
\end{aligned} \tag{10}
$$

Finally, the Nyquist diagram showing stability and phase margins appear in Figure 6.

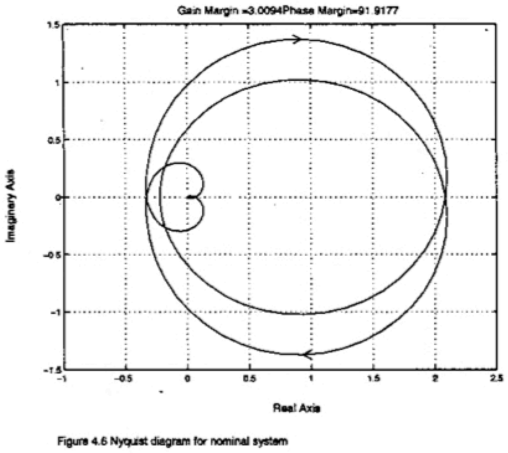

Fig. 6. Controlled system stability and phase margins.

V. Conclusions

A driveline controller model was derived using the pole placement method. Multi objective genetic algorithms were applied to find the optimal location of the poles for the characteristic equation. The definition of the decision variables and objectives was kept in such a way that large search spaces would be avoided. Random initial conditions were applied to each generation to achieve robust solutions. The response of the selected controller shows a dramatic improvement over the open loop response, and also the simple control solution of using a ramp input to the throttle actuator during transients in basically two aspects: the response is faster, and it does not require tuning depending on variations in the system parameters. The controller response also proves to have a better performance than the results obtained in the literature. The combination of the pole placement method with MOGA as a technique for driveline controller optimisation results in an efficient design procedure, where the lack of knowledge of the possible solutions does not necessarily affect the result of design process.

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